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ADP011345

TITLE: Measurement of the Spatial Frequency Response [SFR] of Digital Still-Picture Cameras Using a Modified Slanted Edge Method

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TITLE: Input/Output and Imaging Technologies II. Taipei, Taiwan, 26-27 July 2000

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Measurement of the spatial frequency response (SFR) of digital still-picture cameras using a modified slanted edge method

Wei-Feng Hsu, Yun-Chiang Hsu, and Kai-Wei Chuang

40, Chungshan North Road, 3rd Sec., Taipei, Taiwan 104, ROC

Institute of Electro-Optical Engineering, Tatung University

ABSTRACT

Spatial resolution is one of the main characteristics of electronic imaging devices such as the digital still-picture camera. It describes the capability of a device to resolve the spatial details of an image formed by the incoming optical information. The overall resolving capability is of great interest although there are various factors, contributed by camera components and signal processing algorithms, affecting the spatial resolution. The spatial frequency response (SFR), analogous to the MTF of an optical imaging system, is one of the four measurements for analysis of spatial resolution defined in ISO/FDIS 12233, and it provides a complete profile of the spatial response of digital still-picture cameras. In that document, a test chart is employed to estimate the spatial resolving capability. The calculations of SFR were conducted by using the slanted edge method in which a scene with a black-to-white or white-to-black edge tilted at a specified angle is captured. An algorithm is used to find the line spread function as well as the SFR. We will present a modified algorithm in which no prior information of the angle of the tilted black-to-white edge is needed. The tilted angle was estimated by assuming that a region around the center of the transition between black and white regions is linear. At a tilted angle of 8 degree the minimum estimation error is about 3%. The advantages of the modified slanted edge method are high accuracy, flexible use, and low cost.

Keywords: Digital still-picture cameras, spatial resolution, spatial frequency response, modulation transfer function, slanted edge method

1. INTRODUCTION

The spatial resolution capability, one of the most important attributes, of an electronic still picture camera is the ability of the camera to capture fine details found in the original scene. For electronic still picture cameras the resolving ability depends on many factors, including the performance of the optical imaging lens system, the number and the pitch of camera sensing photodetectors, as well as the electrical circuits of the functions including the gamma correction function, digital interpretation, color correction, and the image compression. There are different measurement methods which provide different metrics to quantify the resolution of an electronic camera. These metrics contain visual resolution, limiting resolution, spatial frequency response (SFR), modulation transfer function (MTF), optical transfer function (OTF), and aliasing ratio. The SFR depicts the frequency response at all spatial frequencies of a digital still-picture camera. A standard SFR algorithm employing the slanted-edge method is adopted in ISO 12233 in which a test chart containing some black-to-white and white-to-black edges, tilted at certain angles, is used to evaluate the SFR [1], [2]. In the selected region of the chart image, each row of the edge spread image is an estimate of the camera edge spread function (ESF). Each of these ESFs is differentiated to form its discrete line spread function (LSF). To accomplish this, it is first to find the position of the centroid of each row LSF which is used to find the shift of this LSF to a reference origin. It then needs to truncate the numbers of rows of data to a full cycle of rotation. The next step is the super-sampling and averaging to form a compositive requantized ESF over a discrete temporal variable which is four times more finely sampled than the original ESF. The averaged, super-sampled ESF is then differentiated and windowed to yield the LSF. The SFR is obtained using the normalized discrete Fourier transform of the single line spread function.

We have developed an algorithm to estimate the angle of a tilted edge and then to find the SFR using the curve fitting

In *Input/Output and Imaging Technologies II*, Yung-Sheng Liu, Thomas S. Huang, Editors, Proceedings of SPIE Vol. 4080 (2000) • 0277-786X/00/$15.00

technique by applying a mathematical model analog to the edge variation. This SFR algorithm can be applied to any test chart containing edges slanted at arbitrary angles and provide high accuracy of the SFR measurements of commercial still cameras. Without necessarily knowing the angle of a particular test chart in advance or precise alignment between the test chart and the camera, this algorithm can easily be used both in the lab and in the field.

2. THE SFR ALGORITHM

Figure 1 shows a flowchart of the algorithm developed for this study. The key issue of finding a precise SFR is the estimation of a correct shift of the scanning row with respect to the camera sensor grid on the chart image. The estimation of the position shift in the ISO algorithm is achieved locally by finding the difference between the closest pixel to the Centroid on each row and the Centroid. Unlike the ISO algorithm, the presented algorithm calculates the row shift from global data by finding the tilted angle between the edge and the sensor grid.

In this algorithm, after an edge area is determined, the Centroid of the area is obtained from the whole area in order to minimize the effect of random noise. The next step is to find the edge slopes on each sensor row and column (in the horizontal and vertical directions) that crosses the edge. These slopes should be found at the half of the edge height. However, the half-height slope cannot exactly be found because of the discrete nature of digital cameras. To solve this problem, those pixels with a value close to the Centroid would be used only, and the slopes are calculated from those pixels. We first set a small region, called the linear region, on each row and column around the Centroid and look for enough pixels to estimate a slope. If no enough pixels are found to find the slope, the linear region is increased until a valid number of slopes are found. In order to minimize the noise effect, the means of the row slopes and column slopes are obtained. The tilted angle θ of the edge to the sensor row is then obtained by [3]

$$\theta = \tan^{-1}\left(\frac{\text{Mean Slope of the Columns}}{\text{Mean Slope of the Rows}}\right). \tag{1}$$

The row shift is given by

$$\Delta x = Y \cdot \tan\theta, \tag{2}$$

where Y is the pitch in the vertical axis of the camera sensor. Since the row shift is obtained, the sensor rows can be merged by properly shifting to a multiple of Δx to compose a highly sampled ESF. Then, the compositive ESF is curve fitted with a Fermi function

$$f(x) = b + \frac{h}{1+\exp(-w\cdot(x-c))}. \tag{3}$$

Here, b is equivalent to the mean black level on the chart image, h is the height of the ESF, w is the width parameter, and c corresponds to the center of the function. When the curve fitting is accomplished, a set of these parameters can be directly applied to the derivate of the Fermi function

$$f'(x) = -\frac{w\cdot h\cdot \exp(-w\cdot(x-c))}{[1+\exp(-w\cdot(x-c))]^2} \tag{4}$$

which yields a continuous LSF of the edge.

Then, the curve fitting technique is employed to model the sharp of the edge transition, or the edge spread function (ESF), with the Fermi function [3], and yields a set of the parameters b, h, w and c. The continuous line spread function (LSF) is found by directly differentiating the obtained ESF and substituting these Fermi parameters into the differentiation of ESF. The continuous LSF is sampled by a frequency that is four times of the original sampling frequency in which the multiple of four is designated by ISO. Finally, the super-sampled LSF sequence is discrete Fourier transformed to generate the SFR of the test camera.

Input to this algorithm is a two-dimensional array containing the digital data of an image of a slanted edge. The size of this image array needs to consist of enough rows of data, typically more than 10 rows, and black and white areas, each more than 1/4 of the slanted edge image. The simulations were achieved using MATLAB programs.

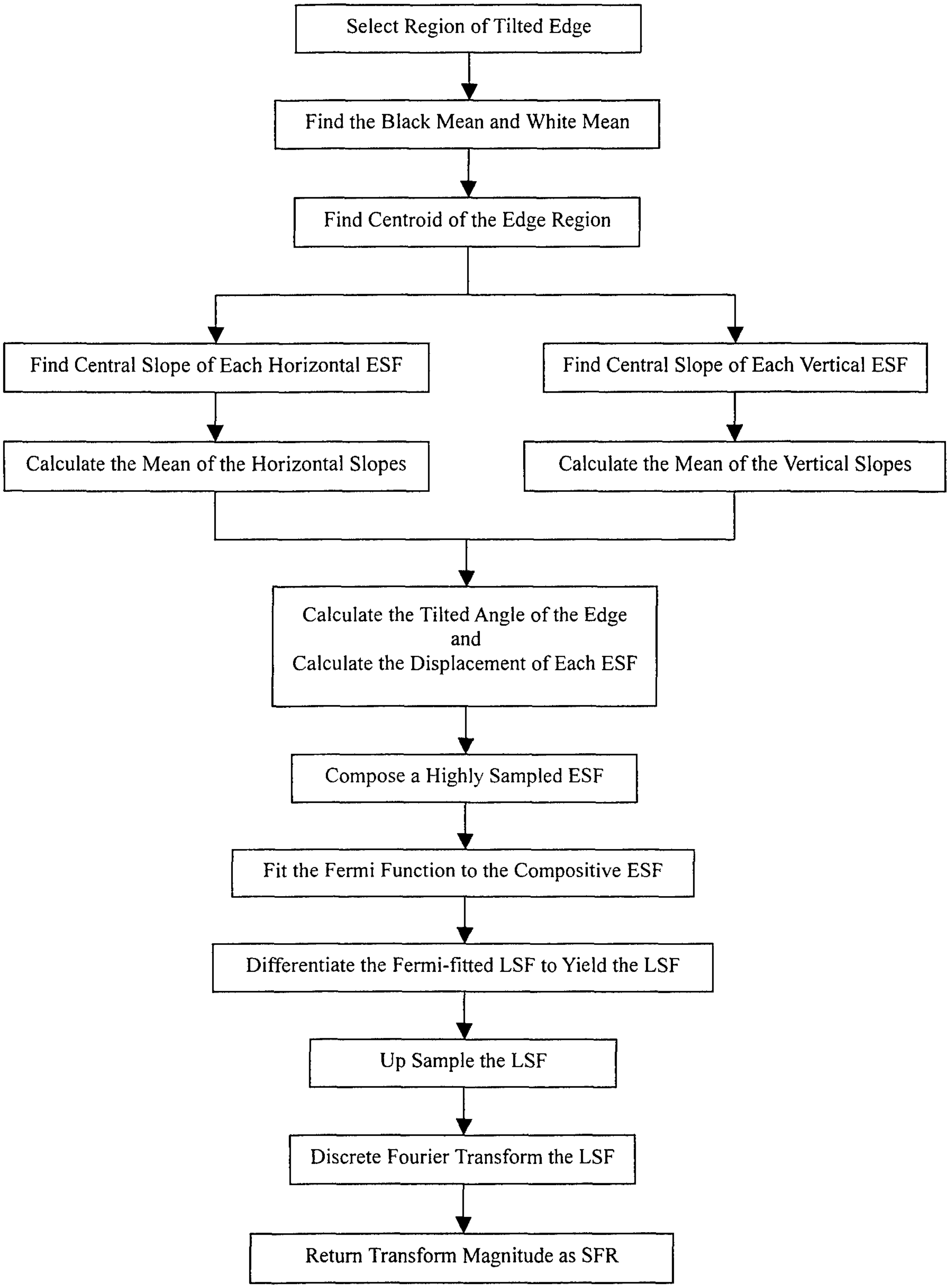


Figure 1. Flowchart of SFR measurement algorithm

3. SIMULATION RESULTS

We first generated a sequence of images on which a black-to-white edge is tilted at angles of 5 to 80 degrees at an interval of 5 degrees. These edge images were sampled by assigning a set of the sensor pitches and pixel dimensions in to simulate the sampling process of a digital camera. The SFR algorithm is applied to an image of a black-to-white edge tilted at an angle ranging from 5° to 20°. Figure 2 shows the simulation of an image of the tilted edge that was generated by a computer. Each square on this image represents an area where its optical power is collected by a CCD sensor pixel. The image of the sampling result is shown in Fig. 3(a) and a compositive edge-spread function of the slanted edge in Fig. 3(b) after the algorithm was applied. Here, the estimation of the angle and the selection of the function to model the edge transition are two critical issues to achieve a good approximation of the SFR. Without any noise involved, the estimation of the ESF is quite good as shown. However, various photographic situations such as different tilted angles, pixel pitches and dimensions, signal-to-noise ratios, and contrast ratio all may influence the estimation results and need to be studied in details.

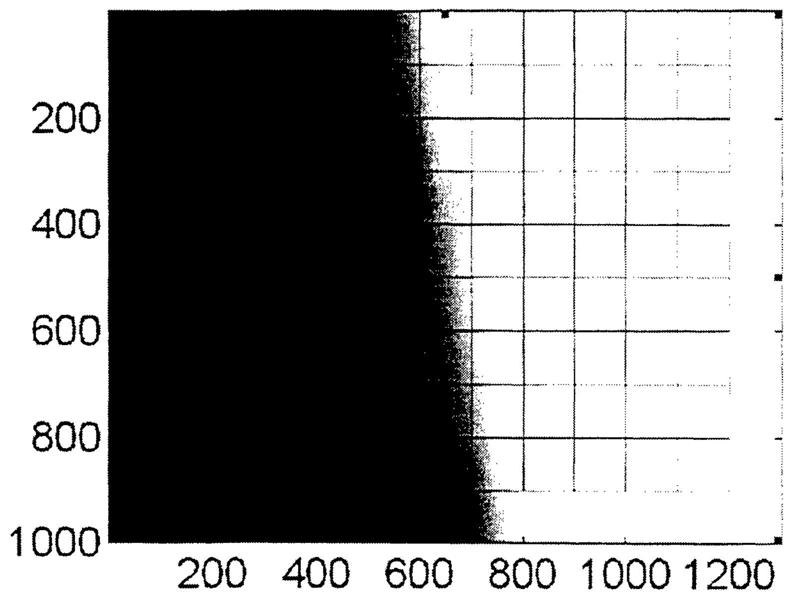
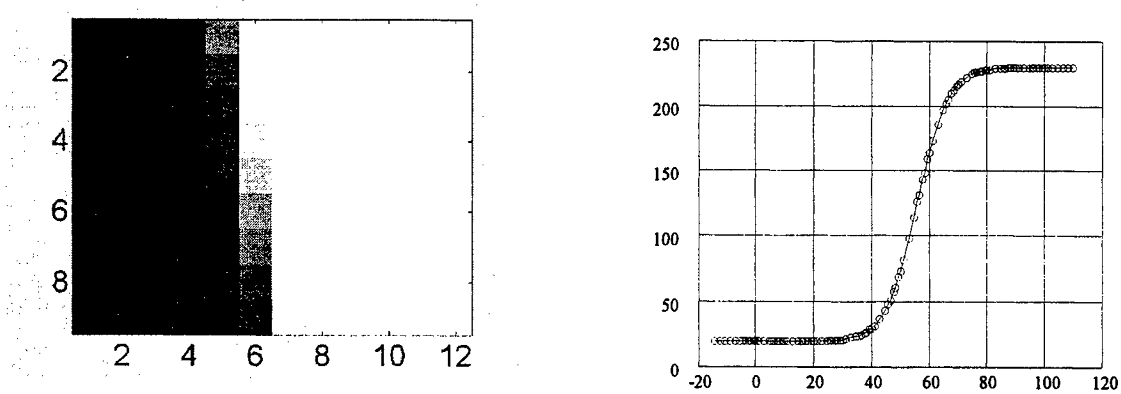


Figure 2. A computer-generated image of the tilted edge



(a) (b)

Figure 3. (a) The edge image after sampled and (b) a compositive edge spread function

3.1 Tilted angle

The SFR algorithm was first used to find the angle of edge which is tilted from 5° to 80° in an interval of 5°, and the estimation results are shown as in Fig. 4. Figure 4(a) depicts the estimation angles to the given angles and their RMS errors in Fig. 4(b). The smaller RMS errors occur at small (less than 20°) and large (larger than 70°) angles, as well as in the middle 45°. Because the vertical (column) and the horizontal (row) slopes are calculated in the same way, the estimation angle should not vary significantly in the symmetric angles to 45°, e.g. 10° and 80°, or 15° and 75°. It is suggested according to the observation of Fig. 4 that the angles in the range of 5° to 20° provide a good estimation result to the tilted angle for this algorithm. It is noticed that the RMS error at the tilted angle 45° is also small. Nevertheless, it is not preferred here fro the reasons discussed later.

3.2 Pixel pitch and dimension

In the simulation, the width of the edge transition is designed to be 46 μm for the digital level varying from 1% to 99% of the edge height. The variables *W*, *D*, and *d* denote the width of the edge, the pixel pitch, and the pixel dimension, respectively. The estimation results of three tilted angles (10°, 30°, and 45°) are shown in Fig. 5. The normalized sampling period is defined as the ratio of the pixel pitch to the edge width, i.e., D/W. In Fig. 5(a), the RMS error increases as the normalized sampling period increases. The errors of the edge tilted at 45° vary greatly at $D/W \approx 0.5$. A tilt of 45° results in a shift of a half of the pixel pitch and thus only a sampled pixel locates in the edge transition region. The poor sampling process occurs both at the vertical and horizontal directions and results in large RMS errors. It is one of the reasons that 45° tilted angle is not preferred.

Figure 5(b) shows the RMS error of the estimations for various aspect ratios, defined as the ratio of the pixel dimension (*d*) to the pixel pitch (*D*). The RMS error slightly decreases as the aspect ratio increases for the tilted angles of 30° and 45°, but remains almost constant for the angle 10°. The aspect ratio does not significantly affect the estimation results for the use of this algorithm.

3.3 Signal-to-noise ratio

It would be important and practical to analyze the performance of the presented algorithm when it is applied to an image containing noises. The RMS error versus the signal-to-noise ratio (SNR) is shown in Fig. 6. It is observed that the RMS error does not change significantly even the SNR is as low as 5 for the tilted angles of 10° and 45°, and it only roughly decreases as SNR increases for the tilted angle 30°. This algorithm is immune to the noise effects due to the use of the Fermi function that eliminates the noise variations at the step of curve fitting. Therefore, it is suggested that smaller tilted angles around 10° would be preferred in this algorithm.

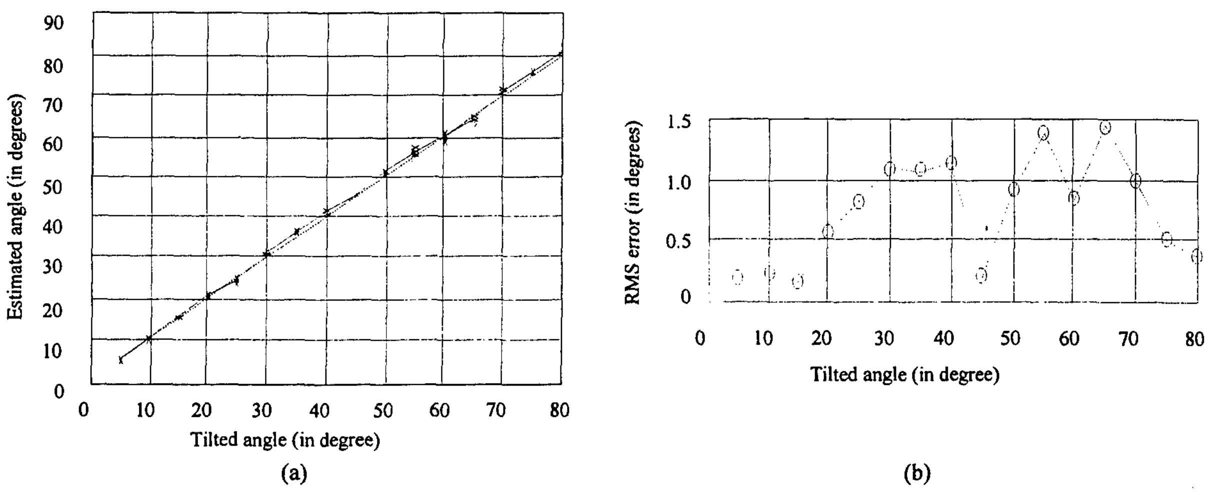


Figure 4. (a) Estimations of the tilted angles and (b) the RMS errors

3.4 Contrast ratio

The contrast ratio is defined as the ratio of the brightness of the white area to that of the black area. As shown in Fig. 7, the estimated angle approaches to the real tilted angle for the contrast ratio greater than a value depending on the tilted angle. The value decreases as the tilted angle decreases. The edge of a tilted angle of 10° in an image of a contrast ratio as low as 5 can be precisely estimated using this algorithm.

3.5 Estimation of the spatial frequency response (SFR)

The estimation of the spatial frequency response of the edge image is shown in Fig. 8 in which the dashed line denotes the SFR of a perfect edge. In the test images, the edge is tilted at 10° and the SNR is given from 5 to 20. The estimation error is the difference between the estimated SFR and the perfect SFR at the modulation of 0.05. The spatial frequency at

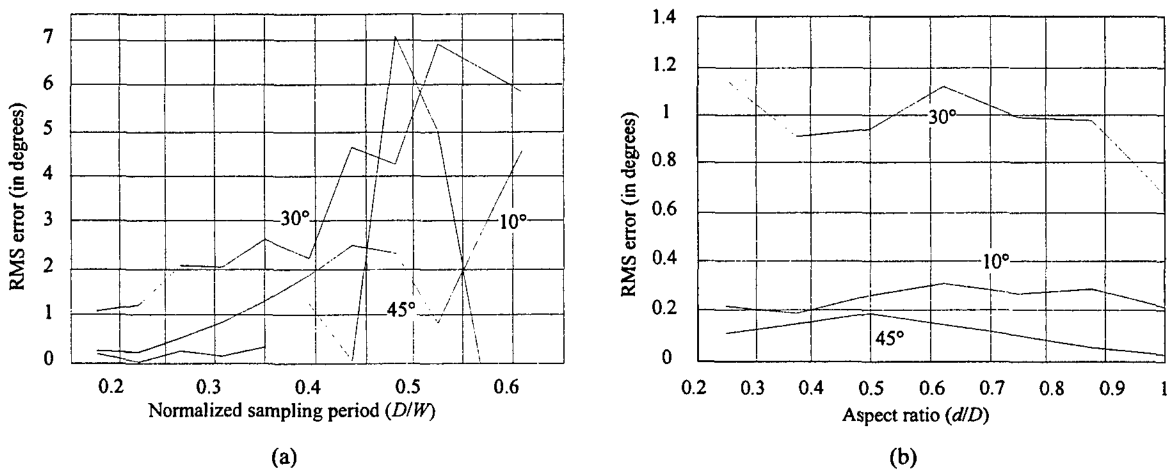


Figure 5. (a) The RMS error versus the normalized sampling period (at a fixed aspect ratio of 1) and (b) the RMS error for different aspect ratio (at normalized sampling period 0.17, $D = 8\ \mu m$)

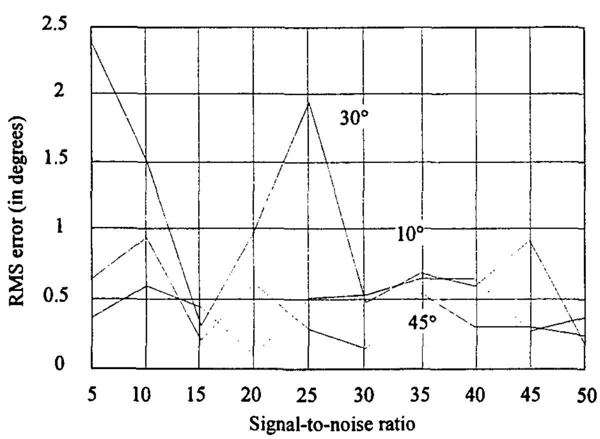


Figure 6. The RMS errors for different signal-to-noise ratio (at the fixed aspect ratio 1 and the normalized sampling period 0.17)

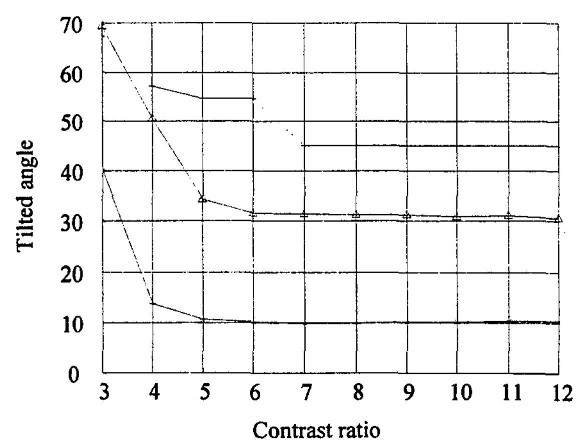


Figure 7. The estimation of the tilted angles for different contrast ratio (at the fixed aspect ratio 1 and the normalized sampling period 0.17)

Table 1. Estimation of the SFR of the edge tilted at 10°

SFR	Standard	SNR = ∞	SNR = 5	SNR = 10	SNR = 15	SNR = 20
Frequency at the modulation 0.5 (lp/mm)	26.3	25	27.4	23.9	24.1	24.2
Frequency error (lp/mm)	--	1.3	1.1	2.4	2.2	2.1

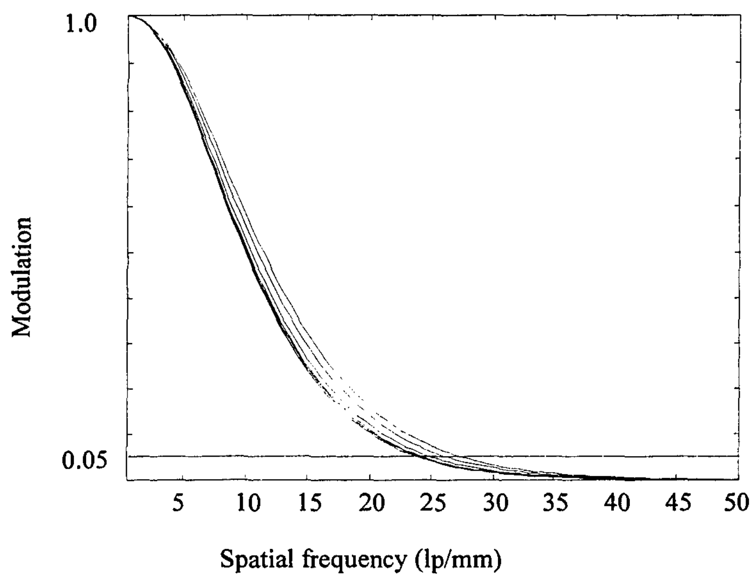


Figure 8. Estimation of the SFR for images of SNR = 5,10, 15, 20, and ∞

the modulation 5% is used as the reference because the limiting resolution, one of the resolution metrics [4], is defined as the spatial frequency at a modulation of 0.5. It is noticed that all the frequency errors are less than 2.5 line-pairs per millimeters (lp/mm) as listed in Table 1. Note that the pixel pitch is 10 μm and thus the Nyquist frequency is 50 lp/mm

4. CONCLUSIONS

The presented algorithm can be applied under various measurement environments since the angle information is not required for the estimation of the camera SFR and, therefore, no official test chart is needed. According to the simulations of the algorithm, it is suggested that the angle should be tilted between 5° through 20°. Although, the best estimation result occurs at the angle tilted at 45°, the edge of tilted angle 45° is not preferred because the estimation of the 45° angle cannot provide a stable estimation at normalized sampling periods around 0.5 and when noise happens to corrupt the single sampled pixel in the edge region. In conclusions, the advantages of the proposed algorithm are:

1. It can be used in low signal-to-noise ratio.
2. It can be used in low contrast ratio.
3. The cost of the test chart is low.

ACKNOWLEDGMENTS

This work was supported in part by Tatung University, Taipei, Taiwan, R.O.C. under the grant B87-1011-01.

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